

Network Controlled Mobility Management using IP over ICN Architecture

Mohammed Al-Khalidi, Nikolaos Thomos, Martin J. Reed, Mays F. AL-Naday and Dirk Trossen

Abstract—Efficient mobility management techniques in wireless networks are critical in providing seamless connectivity and session continuity between the user equipment (UE) and the network during mobility. Current wireless networks with different access and core technologies are tending towards network controlled mobility management (NetLMM) and eliminating any UE protocol stack modification to support mobility. This is mainly facilitated through a common mobility support architecture of a central mobility management entity and tunnelling approaches between this entity and the edge access routers to maintain user data session and IP address during mobility. In this paper, we propose a novel NetLMM approach using IP over Information Centric Networks (ICN) that exploits the ICN advantages in terms of decoupling requests resolution from data transfer in both time and space, representing active user sessions as information publications/subscriptions, thus eliminating the need of tunnelling user traffic through a centralized anchor (as in current IP mobility solutions). This approach leads to a reduction in network overhead, while preserving network controlled mobility to achieve efficient handover with minimum cost. We analyse the core network mobility costs in IP over ICN networks using random walks on connected graphs and derive the corresponding cost functions in terms of signalling and packet delivery costs. We compare the mobility costs with those of the IETF standardized NetLMM protocol, Proxy Mobile IPv6 (PMIPv6). We also simulate both IP over ICN and PMIPv6 networks to investigate UE mobility using the two aforementioned core networks. Both analysis and simulation results show the significant gain in the total cost of using an ICN core to facilitate NetLMM mobility for IP end users.

Index Terms—NetLMM, IP over ICN, Proxy Mobile IPv6, GPRS, GSM.

1 INTRODUCTION

THE significant progress achieved in mobile technologies, allowing users to enjoy Internet based content services during movement, relies on mobility management protocols for enabling these mobile services. Mobility management is a challenging research topic since the performance of mobility management protocols will largely affect users' experience in respect of preventing frequent disconnections and ensuring session continuity [1]. The Internet protocol's location dependent end host identification is one of the main difficulties facing mobility in the Internet today. Considering the rising volume of mobile traffic due to increased content streaming, it can be concluded that the problem of mobility will only grow bigger in the near future [2]. As predicted by Cisco, video traffic will compose 80 percent of all consumed Internet traffic in 2019 and traffic from wireless and mobile devices will rise to 66 percent of the total traffic [3].

Conventional IP mobility techniques are based on functions existing in both the mobile terminal and the network to facilitate user mobility. Recently, due to the dominance of mobile traffic over the Internet, the new generation of wireless networks emphasize solutions that relocate mobility functions and procedures from the mobile device to network components. This approach, known as Network-Based Localized Mobility Management (NetLMM), allows

IP devices running standard protocol stacks to move freely between wireless access points belonging to the same local domain. NetLMM is a desirable solution from operator's and stakeholders perspectives because it allows service providers to enable mobility support without any user interaction or UE modification [4] [5]. For this purpose several standards bodies such as the Internet Engineering Task Force (IETF) and Third Generation Partnership Project (3GPP) are expending efforts on establishing reliable and efficient NetLMM services and protocols. However, many challenges still remain to be solved for achieving such a goal [6]. Proxy Mobile IPv6 (PMIPv6) [RFC5213] [7] is the only IETF standardized NetLMM protocol until today and is aimed at accommodating various access technologies such as WiMAX, 3GPP, 3GPP2 and WLAN based access architectures. In PMIPv6, a central Local Mobility Anchor (LMA) is responsible for maintaining reachability to the Mobile Node's (MN's) IP address while the MN moves among Mobile Access Gateways (MAGs) in the PMIPv6 domain by updating the binding cache in a binding table and maintaining a tunnel to the MAG for packet delivery. On the other hand, the MAG is responsible for detecting the MN's movement and initiating binding registration on behalf of the MN [8] [9]. Proxy Mobile IPv6 also supports IPv4 stack and dual stack mobility modes [RFC5844] [10]. Similar procedures are adapted by 3GPP in cellular networks where a mobility management entity (MME) and the General packet radio service (GPRS) Tunnelling Protocol (GTP) [11] is specified to support mobility. GTP is a group of IP-based communications protocols used in the Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS) and Long-Term Evolution (LTE) core networks and is usually decomposed

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into two variations. GTP-U is used to encapsulate user data when passing through the core network while GTP-C is used to carry bearer specific signalling traffic between various core network entities. In 3GPP architectures, GTP and Proxy Mobile IPv6 based interfaces are specified on various interface points [12]. Such mobility management approaches are mainly used to reduce mobility signalling costs in environments with a high mobility rate, but as a consequence they cause extra packet tunnelling overhead and inefficient routing due to central traffic anchoring in the network. Such drawbacks of current IP mobility solutions necessitate the look for better approaches, as in this paper. Information Centric Networking(ICN) [13] [14] has emerged as a novel solution to the location dependent end host communication architecture of the current internet, addressing the increasing needs of an information centric communication architecture that facilitates information dissemination rather than end host communication. A wide range of ICN implementations have been proposed in various research projects [15] [16] [17], of which we choose the Publish Subscribe Internet Technology (PURSUIT) [14] [18] architecture as a reference model. PURSUIT mainly employs a Publish-Subscribe paradigm for information dissemination that names information at the network layer decoupling request resolution from data transfer in both time and space. The asynchronous nature of the Publish/Subscribe architecture simplifies resynchronization after MN handoffs and greatly facilitates mobility by the use of multicast and caching [19]. Clean-slate ICN architecture proposals such as PURSUIT have one significant drawback in that every UE and server networks stack, together with application network interface code, have to be replaced. Therefore IP-over-ICN [20] has emerged as a research effort that aims at enabling individual operators to enhance their services by deploying an IP-over-ICN architecture. IP-over-ICN offers improved services by using an ICN infrastructure without incurring any changes to the user end equipment that uses IP protocol stacks and connectivity.

In this paper we propose a novel NetLMM approach using IP-over-ICN Networks where PURSUIT ICN architecture represents the core of the network and IPv4 communication is facilitated at the edges. In the proposed solution, no traffic anchoring is required to support mobility at the network core, and no UE equipment modification or user interaction is required at the network edges. To evaluate our proposal, we analyse the mobility costs in IP-over-ICN networks using random walks on connected graphs and derive the corresponding cost functions in terms of signalling and packet delivery costs. We compare the mobility costs with those of the IETF standardized NetLMM protocol, Proxy Mobile IPv6 (PMIPv6). We also conduct a discrete event simulation of both IP-over-ICN and PMIPv6 networks to investigate UE mobility using the two aforementioned cores and verify the theoretical analysis.

The rest of the paper is structured as follows. Section 2 provides an overview of IP-over-ICN network architecture. Section 3 shows how mobility is managed in IP-over-ICN networks. Section 4 explains why IP-over-ICN is a better approach for NetLMM. Section 5 includes the detailed mobility modelling and cost analysis used in the evaluation of the proposed mobility management solution. Section 6

discusses the obtained modelling and simulations results, while a survey of related work is provided in Section 7. A discussion and comparison of NetLMM mobility approaches is presented in Section 8. And finally the paper is concluded in Section 9.

2 IP OVER ICN NETWORKS

The proposed IP-over-ICN architecture follows a gateway-based approach, where the first link from the user device to the network uses existing IP-based protocols, such as HTTP, CoAP, TCP or IP, while the Network Attachment Point (NAP) serves as an entry point to the ICN network and maps the chosen protocol abstraction to ICN. The ICN core employs a Publish-Subscribe paradigm for information dissemination that names information at the network layer, arranging individual information items into a context named scoping. Scopes allow information items to be grouped according to application requirements for example different categories of information. Relationships between information items and scopes are represented as a directed acyclic graph of which leaves represent pieces of information and inner nodes represent scopes. Each node in the graph is identified with its full path starting from a root scope, a more detailed explanation is given in [18]. There are three main functional entities that compose the ICN architecture as shown in Fig. 1. Namely, the Rendezvous (RV) that is responsible for matching publications and subscriptions of information items. The Topology Manager (TM) that is responsible of constructing a shortest path delivery tree for the information object. This delivery tree is encoded in a forwarding identifier (FID) which is sent to the publisher to forward the packets containing the information object to the subscriber. In the network, there are also Forwarding Nodes (FN) that simply forward the information object to the subscriber using the specific FID generated for this transmission [21]. Throughout this paper, the TM and RV functions are assumed to be residing in the same entity for simplicity.

The IP-over-ICN operation uses publish/subscribe semantics for carrying IP datagrams over the ICN network. First a, naïve, pub/sub signalling description will be given, to show the underlying principle, although in a likely deployment there will be optimizations to this naïve signalling that will be later explained. Those readers new to ICN may find the signalling sounds complex, however we tend to forget that a basic IP network application requires a combination of DHCP and DNS signalling to allow IP communication, the ICN signalling may be likened to this support signalling. However, unlike a paper describing a pure IP application this work needs to describe the detail as it is assumed to be new to most readers. Later we will find that the ICN approach can significantly reduce the overall traffic cost in the network.

2.1 A naïve ICN signalling approach

To explain the underlying IP-over-ICN principle we will here describe a naïve signalling approach, as described by Trossen *et al.* [20]. ICN uses a namespace to facilitate communication, this namespace may be used to represent any

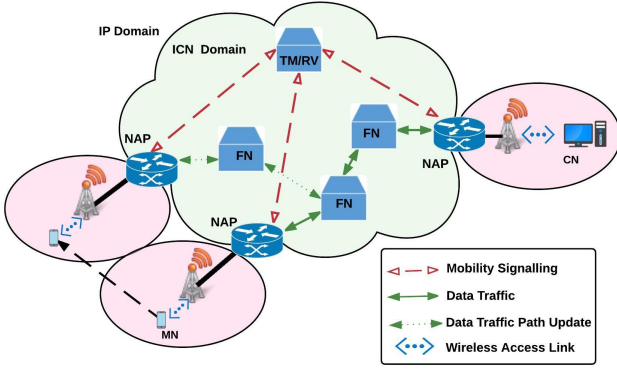


Fig. 1: IP-over-ICN Architecture and Mobility Management Overview

form of information. In an IP-over-ICN scenario an IP address simply becomes an ICN name and the NAP uses publish/subscribe semantics to enable the sending/receiving of IP datagrams. To aid the description we will consider an IP client connected to what we describe as a client NAP (cNAP) and an IP server connected to a server NAP (sNAP). The cNAP and sNAP are only descriptive notations used for the naïve description, in practice a NAP will perform functions for any client or server connected to it so that, in practice, a NAP performs as both a cNAP and sNAP. An sNAP providing connectivity to an IP server is said to *subscribe* to receive packets destined for the IP server, this subscription state is registered in the domain RV. Then if an IP client wishes to send data to the IP server the cNAP is said to *publish* the IP datagrams to the IP server NAP. To actually forward the IP datagrams, the cNAP requires an FID for the forwarding function and this FID is obtained through pub/sub matching. Pub/sub matching occurs in the RV when both a publisher and subscriber are registered for a unique ICN name, in this case the ICN name is the server IP address. Thus, when the cNAP registers the publication to the RV the RV notes the match and requires the TM to send an appropriate FID to the cNAP so that it can publish (transmit) the data to the sNAP. In the naïve approach when the IP server replies this whole mechanism can be reversed so that IP datagrams can flow in the reverse direction as well. When the client/server stop communicating (e.g. after a TCP FIN or after a suitable time-out) the publish/subscription matching state can be removed from the RV as communication is no longer required. The server subscription state is still maintained so that future IP clients can start a new communication.

In practice this naïve signalling approach is inefficient in terms of both state requirements in the RV and the number of signalling messages. Consequently, a practical implementation implements signalling optimizations including combining the cNAP publication message with an implicit subscription and only keeping the server subscription state in the RV. These optimizations are included in the signalling described in the following section.

3 MOBILITY MANAGEMENT IN IP-OVER-ICN

For mobility management in IP-over-ICN, we propose that the NAP could serve as a MAG that performs the mobility management on behalf of a mobile node. The NAP occupies a key role in both UE network attachment and IP/ICN abstraction and interfacing. Therefore, it is a natural point for detecting the mobile node's movements to and from the access link since it resides at the access link where the mobile node is attached. On the ICN side, we propose that a centralized TM initially sets up the required routing state in the network and creates FIDs to forward packets from every NAP to every other NAP according to the deployed routing algorithm. All NAPs receive their specified FIDs and populate a local table containing the complete set of FIDs required to reach any other NAP in the network. In IP-over-ICN, the mobile node will receive the IPv4 address that the NAP locally assigns, and the NAP will act on behalf of the mobile node as the publisher or subscriber towards the ICN. The ICN represents the network structure of IP addresses in a namespace under a unique root scope and an IP address of any device is interpreted as an appropriate ICN name under this scope. This means that the NAP will be ready to receive any information being sent to the assigned IP address by determining the appropriate ICN name according to the defined namespace. Therefore, any IP packet being sent to an IP address allocated to an IP device will arrive at the NAP serving it as an ICN-compliant notification to a subscription to this IP address (represented as an appropriate ICN name) [20]. The IP namespace proposed includes a network prefix scope identifier that serves as a root identifier and represents the IP network prefix allocated to serve the subject network domain. Under this root scope, there exists a so-called IP scope that represents the individual IP addresses allocated to IP endpoints that exist within the domain. These identifiers are formed by hashing a fully qualified IP address into a single 256 bit identifier.

Fig. 2 shows a sequence diagram of the messages exchanged to establish a session between two IP endpoints in the proposed IP-over-ICN network. In this scenario, we assume that both the mobile node and the corresponding node are in the same network domain. For simplicity the examples assume a single subnet where a MN is likely to keep its IP address when moving among NAPs. The ICN core maintains session continuity by maintaining the same pub/sub matching relations at the rendezvous even when a MN moves from one NAP to the other. This forms one of IP-over-ICN advantages compared to Proxy MIPv6 networks for intra-domain scenarios because scalability is maintained by dividing and regionalising the broadcast domain behind NAPs and routing is done through the ICN infrastructure using ICN semantics. This removes the scalability restrictions that would exist in an IP-core that would have to route /32 host-routes for every host in the domain. In the IP-over-ICN case the external IP network could be divided into subnets (maybe for address allocation reasons) and the IP-over-ICN will treat the IP addresses in the same manner as a single subnet as

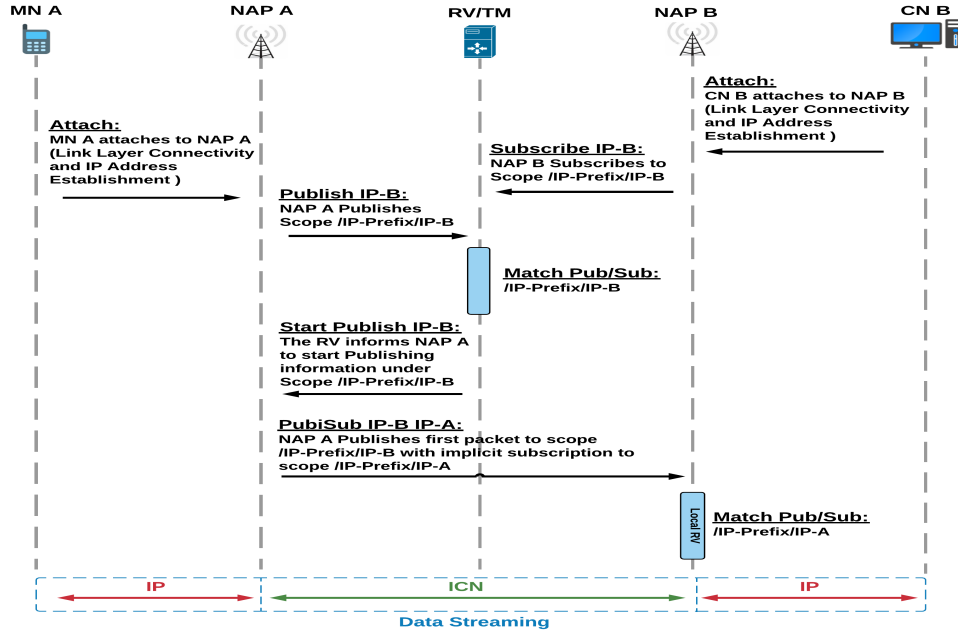


Fig. 2: Sequence Diagram of Session Establishment in IP-over-ICN Networks

forwarding within the ICN is orthogonal to the IP address allocation. For IP-over-ICN networks, end-node IP address sustainability can be maintained using any suitable IP auto configuration mechanism suitable for the network infrastructure deployed. One example is the Dynamic Host Configuration Protocol (DHCP) where every NAP can act as a DHCP server serving the entire subnet deployed in the IP-over-ICN domain. We propose that every DHCP server can be configured to only assign local addresses (for MNs that locally attach to the NAP) from a specific pool within the subnet while it assigns addresses from outside the pool only to MNs that have previously been allocated an IP address at a previous NAP and intentionally ask for this specific IP address at the new NAP. This ensures that no IP address conflict would happen when the MN moves between NAPs. When a MN moves to a new NAP and goes into the DHCP RENEWING state, it would simply send a DHCPREQUEST message including the previously assigned IPv4 home address in the "Requested IP Address" option. The DHCPREQUEST is sent to the address specified in the Server Identifier option of the previously received DHCP OFFER and DHCPACK messages. The DHCP server would then send a DHCPACK to the MN to acknowledge the assignment of the committed IPv4 address [RFC2131] [22], [RFC5844] [10]. Each DHCP server on every NAP is configured to have the same IP address throughout the network, enabling the DHCPREQUEST message to be automatically sent to the available DHCP server on the access link without any delay. To facilitate IP address reuse, we propose that the Rendezvous keeps track of all IP addresses used to maintain pub/sub relations in the network and sends periodic reports to all DHCP servers notifying them of abandoned IP addresses.

In the aforementioned scenario, MN A attaches to NAP

A (Link Layer Connectivity and IP Address Establishment) and then NAP A extracts from the first packet sent from MN A towards MN B the source and destination IP address. NAP A then translates the extracted addresses into appropriate ICN names according to the defined IP namespace. Accordingly, NAP A Publishes the destination address Scope /IP-Prefix/IP-B to the domain Rendezvous on behalf of MN A. Upon receiving this publication, the Rendezvous then matches it with a previous subscription of NAP B to the same scope on behalf of CN B. The Rendezvous triggers NAP A to start publishing information to the identified subscriber located at NAP B. NAP A then looks up its local database for the appropriate FID to reach NAP B and uses it to send a PubiSub message directly to NAP B that includes the first data packet destined from MN A to CN B in addition to an implicit subscription to MN A's own scope /IP-Prefix/IP-A. NAP B utilizes its local Rendezvous to maintain a match pub/sub relation for scope /IP-Prefix/IP-A, looks up its local database for the appropriate FID to reach NAP A and uses this FID to start publishing information to the identified subscriber located at NAP A. At this point MN A and CN B can commence data exchange. This procedure is only required for the first data packet exchange between the two IP endpoint's. Subsequent data packets can be directly sent using the allocated FIDs.

Fig. 3 shows a sequence diagram of the messages exchanged to manage a handover procedure for MN A from NAP A to NAP C. After initiating the handover procedure, the NAP on the previous link (NAP A) signals destination NAP B by sending an iUnsub message on behalf of MN A for its own scope /IP-Prefix/IP-A. This way the local Rendezvous at NAP B can remove the subscription state for MN A. According to this example scenario, MN A re-attaches to NAP C and re-establishes Link Layer Connectivity and IP Address allocation through DHCP which

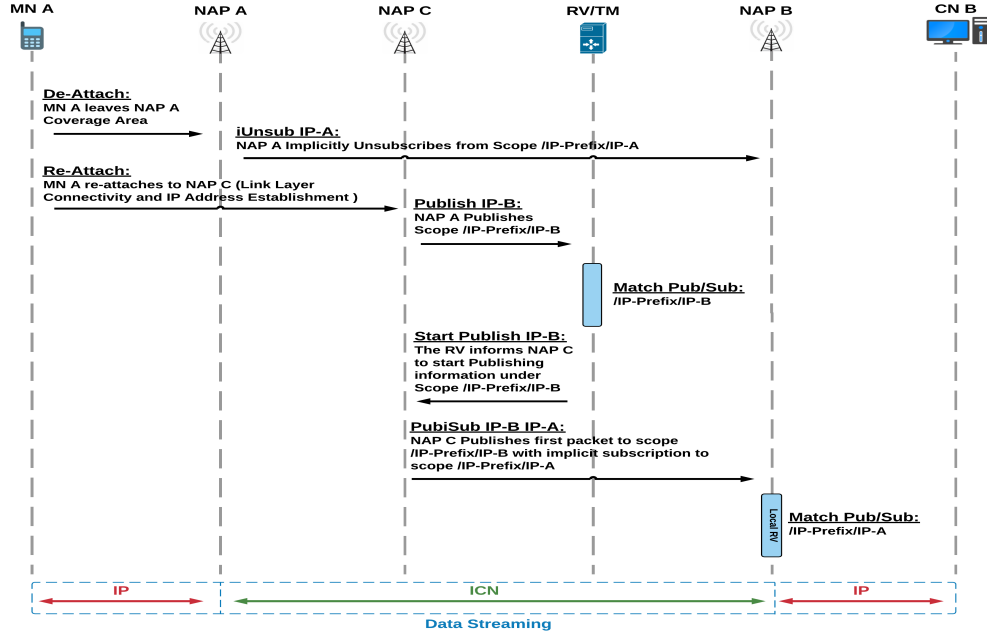


Fig. 3: Sequence Diagram of Handover Management in IP-over-ICN Networks

triggers NAP C upon receiving the first IP packet from MN A to Publish the destination Scope /IP-Prefix/IP-B to the domain Rendezvous on behalf of MN A. The RV at this point re-matches the same publications and subscriptions established previously and triggers NAP C to start publishing information to the identified subscriber located at NAP B. NAP C then looks up its local database for the appropriate FID to reach NAP B and uses it to send a PubiSub message directly to NAP B that includes the first data packet destined from MN A to CN B in addition to an implicit subscription to MN A's own scope /IP-Prefix/IP-A. NAP B utilizes its local Rendezvous to maintain a match pub/sub relation for scope /IP-Prefix/IP-A, looks up its local database for the appropriate FID to reach NAP C and uses it to start publishing information to the identified subscriber located at NAP C. At this point MN A and CN B can commence data exchange without further disruption using MN A's new location. Fig. 1 shows the participating entities and communication message flows for each of the control and data planes during mobility.

On the link layer connectivity, a number of metrics exist to indicate the quality of connection and are used to indicate mobility is occurring. One of these metrics is the Received Signal Strength Indicator (RSSI) which we use in this example – alternatively some other predictor of mobility could be used but for simplicity this is not considered here. The RSSI value is part of the data transmitted by all mobile user equipment units. It is intended as a mean to obtain a relative indication of the quality of connection that exists between the UE and the network access point it is connected to on the wireless network. This could be used as the trigger for movement described in this example. Which NAP a client connects to is almost entirely determined by the MN itself. Thus, when a client is given a choice between multiple NAPs offering the same service, it will always choose the

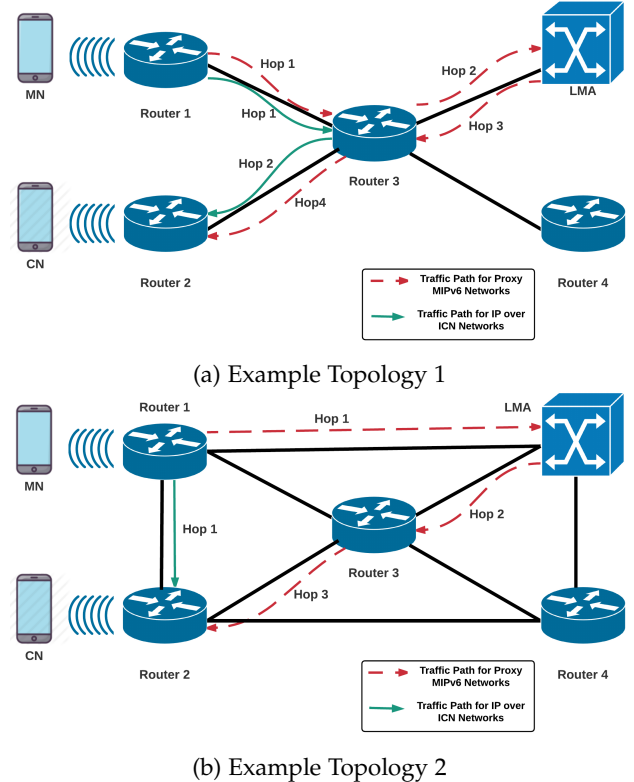


Fig. 4: Packet Delivery Routes in IP-over-ICN vs Proxy MIPv6 Networks.

NAP with the highest RSSI. On the other hand just like the initial association sequence, when a UE is moving it also uses RSSI to determine when to disassociate from a NAP and associate with another.

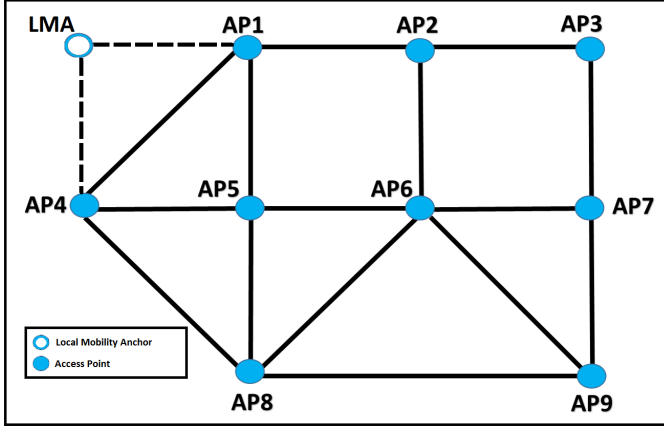


Fig. 5: Network model example

4 WHY IP-OVER-ICN FOR NETLMM ?

Proxy MIPv6 uses a centralized mobility management entity on both the data and control plane to facilitate network based mobility support. This approach on the one hand helps to reduce signalling costs in high mobility rate environments but on the other hand increases traffic and packet delivery cost within the networks core. Using this approach, all traffic sent to and from a mobile node is driven through a local mobility anchor (LMA) that keeps track of the mobile nodes location and routes the traffic accordingly. This approach leads to using sub-optimal routes for packet delivery, thereby increasing the traffic overhead and end-to-end delay. The problem is evident, for example, when accessing a nearby server of a Content Delivery Network (CDN), or when receiving locally available IP multicast packets or sending IP multicast packets. IP-over-ICN on the other hand only requires a central point for mobility signalling and delivery path creation, while the actual payload is delivered from source to destination through the shortest path without any anchoring.

To show the overhead caused by traffic anchoring in a simple way, we use the example in Fig. 4. As shown in the example, for a packet sent from a mobile node (MN) to reach a corresponding node (CN) in Fig. 4a it crosses two routers (hops) in an IP-over-ICN network while it crosses 4 hops in Proxy MIPv6 networks to support network controlled mobility. Thus, the packet delivery cost using IP-over-ICN is half the cost of Proxy MIPv6 using this topology. The gain shown in this example has proven to be topology dependant as can be seen in Fig. 4b. Where the number of hops crossed in an IP-over-ICN network is one hop versus three hops in Proxy MIPv6 networks. Therefore packet delivery cost in this IP-over-ICN scenario is one third the cost of the Proxy MIPv6 solution due to the fact that more links have been added to the same setup. An extended evaluation of network topology effect on router-level internet performance has been shown in [23] and verified that many different graphs having the same distribution of node degree, may be considered opposites from the viewpoint of network engineering and result in widely varying end user bandwidths and router utilization distributions.

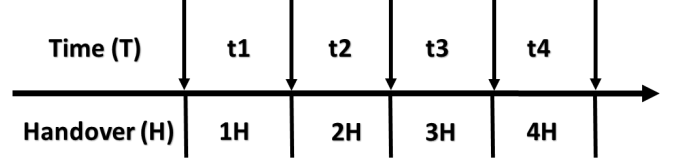


Fig. 6: The Handover Time Diagram

5 MOBILITY MODELLING AND COST ANALYSIS

In order to analyse the mobility behaviour of mobile nodes in Proxy MIPv6 and IP-over-ICN networks, a random walk mobility model is applied on connected graphs that represent the network topology in terms of wireless access points. This approach has been chosen due to the importance of the network topology and its influence on the total cost as described in the previous section. Fig. 5 shows an example network topology graph of 10 nodes that will be used to explain the details of the analysis performed. Given a random starting point, we select a random neighbour to move into (assuming equal transition probability to any neighbour), then we select a neighbour of this new point at random, and move to it etc. The random sequence of points selected this way is a random walk on the graph. A random walk on a network graph of access points possesses some unique distinctive properties that can be pointed out, including that of spatial homogeneity. This means that the transition probability between two points (x and y) on the graph should depend on their relative positions in space. This is obviously due to the fact that a mobile user can only move to a neighbouring access point from any access point he is attached to at any given time. Also this implies that this random walk demonstrates the skip-free property, namely that to go from point x to point y it must pass through all intermediate points because it can only move one point at each step. In our analysis the wireless network is modelled as a connected graph whose nodes represent the coverage areas. This allows for flexibility in topology formation and cell shape assumptions from square and hexagonal cells to completely random topologies. Using a random walk on a connected graph to model user mobility leads to the discrete time finite Markov chain which provides a very practical and reliable way of estimating the location and direction probabilities of a moving user. The location probability represents the likelihood that a MN is located within the range of a specific access point at a given point in time, while the direction probability represents the likelihood that a MN is moving into the coverage area of a specific neighbouring access point within the given set of neighbouring access point at a given point in time. The Markov chain will be used to derive the global balance equations and also to introduce mobility rates into our mobility analysis. A random walk on a connected and undirected graph can be represented as follows [24]:

TABLE 1: Direction Probability Matrix and Steady State Probabilities

AP's	AP1	AP2	AP3	AP4	AP5	AP6	AP7	AP8	AP9	Steady-State Probability
AP1	1/4	1/4	0	1/4	1/4	0	0	0	0	0.100
AP2	1/4	1/4	1/4	0	0	1/4	0	0	0	0.100
AP3	0	1/3	1/3	0	0	0	1/3	0	0	0.066
AP4	1/4	0	0	1/4	1/4	0	0	1/4	0	0.100
AP5	1/5	0	0	1/5	1/5	1/5	0	1/5	0	0.133
AP6	0	1/6	0	0	1/6	1/6	1/6	1/6	1/6	0.166
AP7	0	0	1/4	0	0	1/4	1/4	0	1/4	0.100
AP8	0	0	0	1/5	1/5	1/5	0	1/5	1/5	0.133
AP9	0	0	0	0	0	1/4	1/4	1/4	1/4	0.100

If $G = (V, E)$ is a connected, non-bipartite, undirected graph where V are vertices that represent network access points and E edges that represent the interconnections between the access points; this graph induces a Markov chain (MC) where the states of MC are the nodes of G . The direction probability depends on the degree of nodes (d) such that

$$P_{i,j} = \begin{cases} 1/(d_{(i)} + 1) & \text{If } j \in \Gamma. \\ 0 & \text{Otherwise.} \end{cases} \quad (1)$$

where Γ represents the set of neighbouring nodes of i . If the direction probability is known in the equation above, there exists a unique steady-state location probability distribution vector $\Pi = (\Pi_1, \Pi_2, \dots, \Pi_N)$, such that $\Pi_i > 0$ for $1 \leq i \leq N$. The steady-state probability vector can be obtained by solving $\Pi = \Pi P$ for Π where P represents the direction probability matrix [25]. From our network model example in Fig. 5, the direction probability matrix and the steady-state probability vector are calculated in table 1 above. On the other hand, the Cell border crossing time Δt is the time required to cross a cell border and trigger handover signalling. The Cell border crossing time represents the timestamps of our Markov Chain transitions and is calculated as follows:

T = Evaluation Time (Analysis Accumulative Time).

If $\Delta t > T$ The mobile user stays within the cell coverage area.

Else if $\Delta t < T$ The mobile user crosses the cell border to a neighbouring cell.

Also Δt is equal to $1/\mu$ where μ is the cell border crossing rate. Fig. 6 shows the relation between handover time and total simulation time using a network graph mobility model. A Markov chain can be represented by a state diagram just as finite state machines are often represented and the transitions for Markov chains are associated with probabilities or Markov processes rates. Accordingly, the mobility on the connected graph above can be represented as a Markov process where states represent traversed network access points and transitions between states represent flows of the Markovian process. Fig. 7 shows a complete Markov chain representation of the network topology example in Fig. 5. The local mobility anchor (LMA) has not been

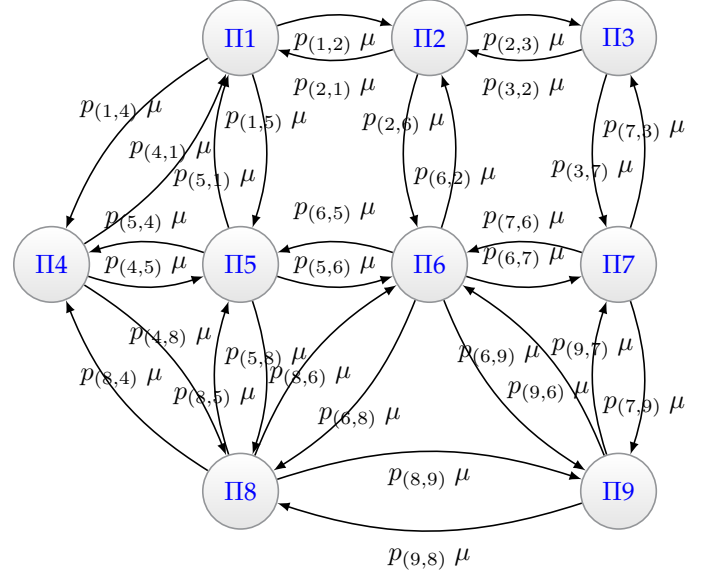


Fig. 7: Network Markov Chain Representation

included in the Markov chain as it is not part of the mobility model and no MN transition into the LMA is permitted.

Assuming a system at steady state, the detailed balance equation for a user at state 1 (Network Access Point 1) would be:

$$3\pi_1 p_{(1,2)}\mu = \pi_2 p_{(2,1)}\mu + \pi_4 p_{(4,1)}\mu + \pi_5 p_{(5,1)}\mu \quad (2)$$

From this point, we represent all of the neighbour cells as a separated Markov state and derive for a common case when a cell k in K total cells has a neighbour cell j in the set of neighbours N_k . We generalize our previous mentioned model to the Markov process shown in Fig. 8 where:

The general global balance equation for the case in equation 2 above can be derived as:

$$|N_k| \pi_k p_k \mu = \sum_{j \in N_k} \pi_j p_{(j,k)} \mu \quad \text{for } 0 \leq k \leq K. \quad (3)$$

Where $|N_k|$ is the cardinality of the set N_k and represents the number of neighbours of cell k and also equivalent to

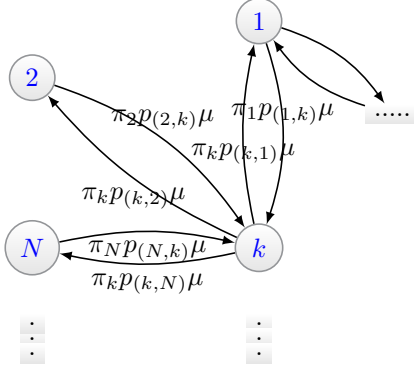


Fig. 8: General Markov Process for Markov Chain Mobility

the node degree in our Markov Chain representation. And p_k represents the direction probability out of cell k where:

$$p_k = p_{(k,1)} = p_{(k,2)} = p_{(k,N)} \quad (4)$$

TABLE 2: List of notations and there description

Notation	Description
μ	Mobility Rate
$p_{(k,j)}$	Direction Probability that a mobile node is moving into MAG j
π_k	Location Probability that a mobile node is attached to MAG k
Ω, Ω'	Total Cost in a PMIPv6, IP-over-ICN Network Respectively
Υ, Υ'	Mobility signalling Cost in a PMIPv6, IP-over-ICN Network Respectively
Λ, Λ'	Mobility packet delivery cost in a PMIPv6, IP-over-ICN Network Respectively.
$h_{k,a}$	Number of hops between the MN initial MAG k and the LMA
$h_{j,a}$	Number of hops between the MN new MAG j and the LMA
$h_{s,a}$	Number of hops between the CN's MAG and the LMA
R, R'	Average packet rate in a PMPv6, IP-over-ICN Network Respectively.
O_k, O'_k	Direct path packet overhead in a PMIPv6, IP-over-ICN Network Respectively.
$h_{j,v}$	Number of hops between NAP j and the Rv/Tm
$h_{k,s}$	Number of hops between NAP k and the destination NAP s
$h_{j,s}$	Number of hops between NAP j and the destination NAP s

5.1 Proxy MIPv6 Mobility Cost Analysis:

Proxy MIPv6 has been used as a reference model to compare the performance of the proposed IP-over-ICN mobility solution. Proxy MIPv6 introduces two main entities that are involved in maintaining network enabled mobility support in a Proxy MIPv6 domain which are the LMA that represents the networks central mobility anchor point and the MAG that acts as a mobility proxy on behalf of the mobile node. In order to update the LMA about the MN's current location, a Proxy Binding Update (PBU) message is sent from the MAG to the MN's LMA.

After accepting this PBU, the LMA sends back a Proxy Binding Acknowledgement (PBA) message to the MN's MAG that includes the MN's home network prefix. It also creates a binding cache entry into its binding cash table and establishes a bidirectional tunnel to the MAG. When the MN changes its point of attachment, the previous MAG on the previous access link detects the MN's detachment from the link and signals the LMA to remove the existing binding and routing state for that MN. The new MAG upon detecting the MN on its access link signals the LMA for updating the binding state. Therefore for every MN transition from one MAG to another, double mobility signalling occurs between the participating MAG's and the domain's LMA [26]. Fig. 9 shows a mobility scenario in a Proxy MIPv6 domain with one MN and a static corresponding node (CN). This scenario is considered in our mobility cost analysis. As it can be concluded from section 4 that no accurate closed form formula can be provided for mobility cost analysis in the investigated environment due to the high dependability of the total cost on the network topological aspects, therefore the mobility cost analysis will be conducted by feeding the influencing topological factors into the cost analysis equations as follows:

The total cost for PMIPv6 Ω can be distinguished into signalling Υ and packet delivery cost Λ and can be expressed as follows: (Please refer to table 2 for a a list of the notations used in this paper)

$$\Omega = \Upsilon + \Lambda \quad (5)$$

where the signalling cost Υ is the signalling overhead for supporting mobility services for a MN. Λ is the packet delivery cost that captures the tunnelling and traffic anchoring overhead. Υ is calculated as the product of the size of mobility signalling messages and the hop distance. While Λ is calculated as the product of the total packet size (including tunnelling overhead) and the hop distance.

The signalling cost Υ in hops.Bytes/s can be calculated as:

$$\Upsilon = \sum_{k=1}^K \sum_{j \in N_k} \left\{ \pi_k p_{(k,j)} \mu (h_{k,a}(L_u + L_a) + h_{j,a}(L_u + L_a)) \right\} \quad (6)$$

where π_k is the location probability of a MN at MAG k and $p_{(k,j)}$ is the direction probability for the MN to move into MAG j coverage area. μ represents the MN's mobility rate of transition. $h_{k,a}$ is the number of hops between the LMA and MAG k and $h_{j,a}$ is the number of hops between the LMA and MAG j. As the MN changes its point of attachment, the previous MAG (MAG k) sends the de-registration PBU message to the LMA in order to inform the detachment of the MN at the access network managed by MAG k. As the new MAG (MAG j) detects the movement of the MN, it registers the MN to the LMA by sending a PBU message. L_u is the size of the proxy binding update (PBU) message sent from the MAG to the LMA and L_a is the size of the proxy binding acknowledgement (PBAck) message. A list of

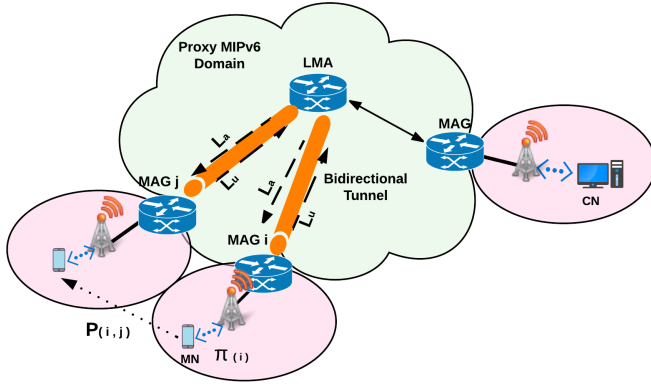


Fig. 9: Node Mobility in a Proxy MIPv6 Domain

mobility messages and their corresponding sizes is shown in table 3. The total size in bytes of proxy binding update and proxy binding acknowledgement can be expressed as

$$L_T = L_u + L_a \quad (7)$$

Therefore substituting with L_T in equation 6 yields

$$\Upsilon = \sum_{k=1}^K \sum_{j \in N_k} \left\{ \pi_k p_{(k,j)} \mu L_T (h_{k,a} + h_{j,a}) \right\} \quad (8)$$

Example 1. Applying the cost function above to the network model example in Fig. 5 yields

$$\Upsilon = 554.462 \mu \text{ hops.Bytes/s}$$

Let us assume a vehicle moving at a velocity of 70 mile/h through a circular coverage area, this would mean that the vehicle spends 25.12 second in every cell it traverses at a mobility rate of 0.039 1/s.

$$\text{Therefore } \Upsilon = 554.462 * 0.039 = 21.624 \text{ hops.Bytes/s} \quad \blacksquare$$

The packet delivery cost Λ is mainly used to investigate the tunnelling and packet delivery overhead and is calculated as the product of total IPv6 packet size (including tunnelling overhead) and the hop distance.

The packet delivery cost for PMIPv6 Λ is expressed as

$$\Lambda = \sum_{k=1}^K \left\{ \pi_k R O_k \right\} \quad (9)$$

Where R is the average packet rate, and O is the direct path packet cost in PMIPv6 and is obtained as

$$O_k = h_{s,a} \zeta + h_{k,a} (\varphi + \zeta) \quad (10)$$

For simplicity we consider the CN a stationary node located at its home cell and therefore it does not incur any

TABLE 3: List of Mobility Messages and their Sizes

Notation	Description	Size
L_u	Proxy binding update (PBU)	76 Bytes
L_a	Proxy binding acknowledgement	76 Bytes
ζ	Average payload length	1024 Bytes
φ	Proxy MIPv6 tunnelling header	40 Bytes
ℓ_u	Implicit Unsubscribe (iUnsub) message	166 Bytes
ℓ_r	Publish Request message	160 Bytes
ℓ_s	Start Publish message	166 Bytes
ℓ_p	Publish with Implicit Subscription message (PubiSub)	166 Bytes
φ'	ICN payload packet header	96 Bytes

tunnelling overhead. Hence $h_{s,a} \zeta$ is the direct path packet cost from the CN to the LMA and is equal to the number of hops between the CN and the LMA $h_{s,a}$ multiplied by the average data packet length in Bytes ζ . On the other hand $h_{k,a} (\varphi + \zeta)$ is the direct path packet cost from the MN (k) to the LMA and therefore the cost is equal to the number of hops between the MN and the LMA $h_{k,a}$ multiplied by the average data packet length in bytes including tunnelling overhead ($\varphi + \zeta$). The complete path packet cost is the sum of the cost between the CN and the LMA and the MN (k) and the LMA.

Example 2. Applying the cost function above to the network model example in Fig. 5 and assuming a stationary CN selected arbitrarily at MAG 7 and a MN receiving video data at a rate of 1 Mbps (123 Packet/s) yields:

$$\Lambda = 809176 \text{ hops.Bytes/s.}$$

Then the total cost for Proxy MIPv6 (Ω) is expressed as follows:

$$\Omega = \Upsilon + \Lambda \quad (11)$$

Therefore the total signalling and packet delivery cost for a MN moving at a velocity of 70 miles/hour in a Proxy MIPv6 domain would be:

$$\Omega = 21.624 + 809176 = 809197.624 \text{ hops.Bytes/s.} \quad \blacksquare$$

5.2 IP Over ICN Mobility Cost

The mobility messages in the proposed IP-over-ICN infrastructure are totally incurred within the ICN core. Fig. 3 shows the sequence of mobility messages that take place during handover in an IP-over-ICN domain. For simplicity we always assume in our analysis that only one end of the communication is mobile (MN) and that the corresponding node (CN) is static and not generating any mobility signalling. After initiating a handover procedure, the NAP on the previous link (NAP A) signals the destination NAP (NAP B) by sending an iUnsub message (ℓ_u) from the MN's own IP address scope. This enables NAP B to gracefully remove the subscription state for MN A from the CN's IP address scope. This state was established prior to the handover at NAP B's local RV. Upon the MN re-attachment to a new NAP (NAP C), and after it

FID 32B	Destination ICN ID 64B		iSub:Source ICN ID 64B		Source EUI48
	Root Prefix Scope	IP Scope	Root Prefix Scope	IP Scope	

(a) iUnsub Message (ℓ_u)

FID 32B	Notification ID 64B		Pub:Destination ICN ID 64B	
	Root Prefix Scope	IP Scope	Root Prefix Scope	IP Scope

(b) Request Publish Message (ℓ_r)

FID 32B	Notification ID 64B		Pub:Destination ICN ID 64B		Dest. EUI48
	Root Prefix Scope	IP Scope	Root Prefix Scope	IP Scope	

(c) Start Publish Message (ℓ_s)

FID 32B	Destination ICN ID 64B		iSub:Source ICN ID 64B		Source EUI48	Variable Size Payload
	Root Prefix Scope	IP Scope	Root Prefix Scope	IP Scope		

(d) PubiSub Message (ℓ_p)

FID 32B	Destination ICN ID 64B		Variable Size Payload
	Root Prefix Scope	IP Scope	

(e) Data Payload Message (ζ)

Fig. 10: IP-over-ICN Message Formats.

establishes layer 2 connectivity and IP address allocation, NAP C receives the first IP packet destined to the CN and sends a Publish request message (ℓ_r) to the domain RV requesting publication to the CN's IP address Scope. Upon receiving the publish request, the RV matches it with a previous subscription to the same address scope requested by NAP B and sends a start publish message (ℓ_s) to the NAP on the new link (NAP C). NAP C then locally looks up the appropriate FID to reach NAP B and uses it to send a PubiSub message (ℓ_p) to NAP B that includes the first data packet from the MN to the CN in addition to an implicit subscription to MN A's own IP address scope. The PubiSub message triggers NAP B to utilize its local Rendezvous to maintain a match pub/sub relation for the mentioned scope, looks up its local database for the appropriate FID to reach NAP C and use it to start publishing information to the identified subscriber. At this point MN A and CN B can commence sending and receiving data payload messages (ζ). Fig. 10 illustrates the detailed message formats and sizes for the mobility messages needed in an IP-over-ICN setup.

The mobility signalling cost is the value of the signalling messages size multiplied by hops. Therefore, the introduced signalling overhead is summarized as follows:

$$\Upsilon' = \sum_{k=1}^K \sum_{j \in N_k} \left\{ \pi_k p_{(k,j)} \mu (h_{k,s} \ell_u + h_{j,v} (\ell_r + \ell_s) + h_{j,s} \ell_p) \right\} \quad (12)$$

where $h_{k,s}$ is the number of hops between the previous NAP k and the destination NAP s, $h_{j,v}$ is the number of hops between the new NAP j and the RV/TM and $h_{j,s}$ is the number of hops between NAP j and the destination NAP s. ℓ_u is the size of an implicit unsubscribe (iUnsub) message sent from NAP k to NAP s when the MN initiates a handover. ℓ_r is the size of a publish request message sent

from NAP j to the RV/TM upon a change in the MN's NAP attachment requesting publication to the destination address scope. ℓ_s is the size of a start publish message sent from the domain RV/TM after a match pub/sub happens triggering NAP j to start sending data packets to NAP s. And ℓ_p is the size of a publish with implicit subscribe (PubiSub) message sent from NAP j towards NAPs including the first data payload in addition to an implicit subscription to the MN's address scope at the new location (NAP j). In the upcoming evaluations the payload size has been excluded from the ℓ_p message size as it is not considered a mobility signalling cost.

Example 3. Applying the cost function in equation 12 above to the network model example in Fig. 5 and assuming a stationary corresponding node selected arbitrarily at NAP 7 and a mobile node k yields:

$$\Upsilon' = 1122 \mu \text{ hops.Bytes/s.}$$

Also assuming the same mobility rate used previously to evaluate the signalling cost of Proxy MIPv6 yields:

$$\Upsilon' = 1122 * 0.039 = 43.758 \text{ hops.Bytes/s.} \quad \blacksquare$$

The packet delivery cost Λ' is mainly used to investigate the packet delivery overhead and is calculated as the product of total packet size and the hop distance. The packet delivery cost for IP-over-ICN Λ' is expressed as follows:

$$\Lambda' = \sum_{k=1}^K \left\{ \pi_k R' O'_k \right\} \quad (13)$$

Where R' is the average packet rate in an IP-over-ICN network, and O'_k is the direct path packet overhead in IP-over-ICN and is obtained as follows:

$$O'_k = h_{s,r} (\varphi' + \zeta) \quad (14)$$

Where $h_{s,k}$ is the number of hops between NAP s where the CN is attached and NAP k where the MN is attached, φ' is the size of the ICN packet header and ζ is the average payload length in Bytes.

Example 4. Applying the cost function above to the network model example in Fig. 5 and assuming a stationary CN selected arbitrarily at MAG 7 and a MN receiving video data at a rate of 1 Mbps (117 Packet/s) yields:

$$\Lambda' = 218400 \text{ hops.Bytes/s.}$$

Then the total cost for IP-over-ICN (Ω') is expressed as follows:

$$\Omega' = \Upsilon' + \Lambda' \quad (15)$$

Therefore the total signalling and packet delivery cost for a MN moving at a velocity of 70 miles/hour in an IP-over-ICN domain would be:

$$\Omega' = 43.758 + 218400 = 218443.758 \text{ hops.Bytes/s} \quad \blacksquare$$

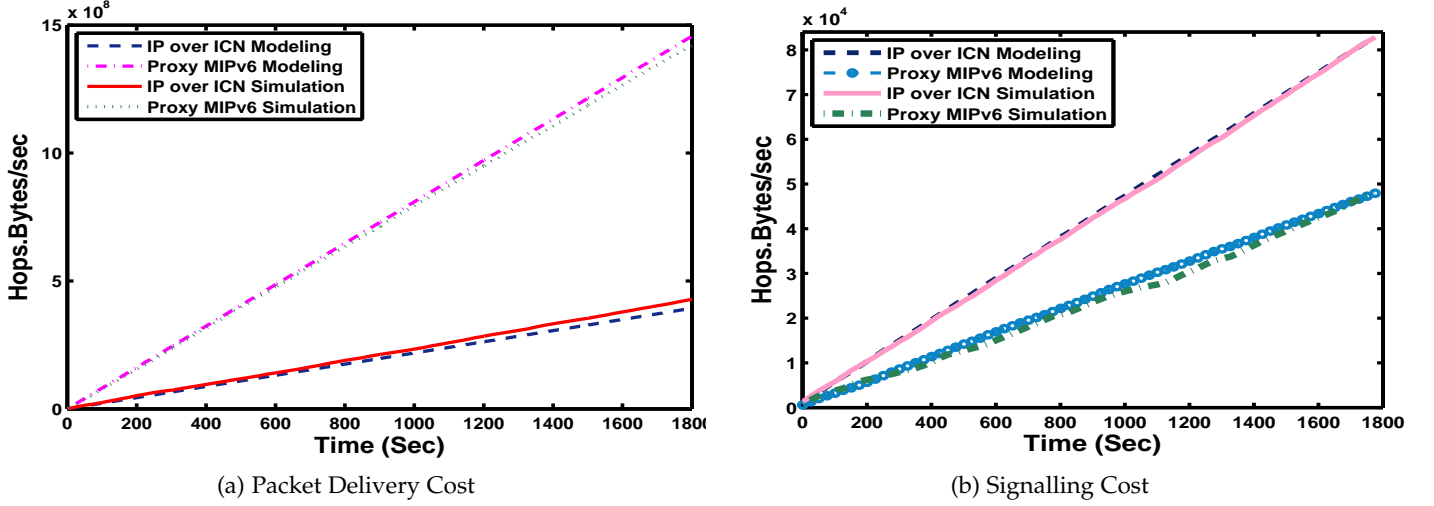


Fig. 11: Modelling and Simulation of a single MN at 70 miles/h with cumulative Cost using the Example Topology of Section 5

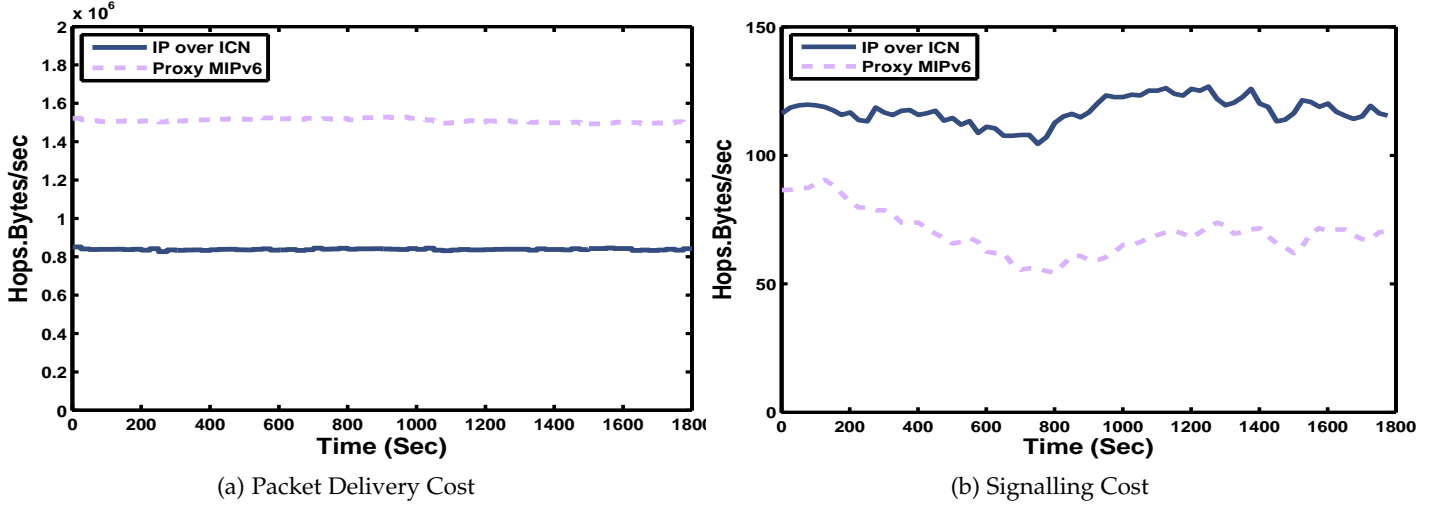


Fig. 12: Single Speed (70 miles/h) Simulation of 50 MNs with Average Cost using a Geometric Random Topology of 100 nodes.

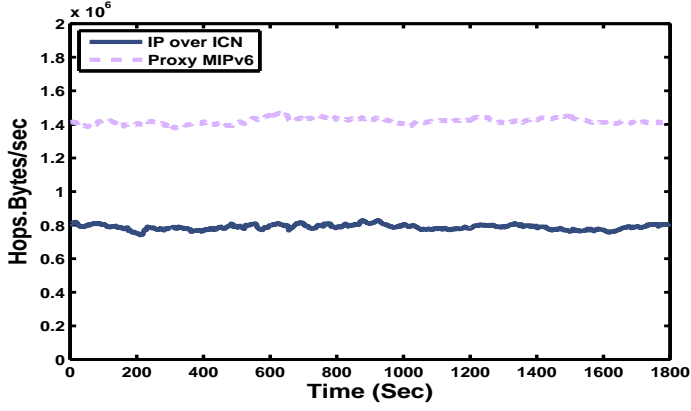
6 MOBILITY MANAGEMENT SIMULATION AND COST EVALUATION

To evaluate the performance of the proposed IP-over-ICN mobility solution and show the significance of the established analytical model, a discrete time event simulation of both Proxy Mobile IP and IP-over-ICN has been conducted. The built simulation environment has been used to investigate the mobility costs (mainly mobility signalling and packet delivery costs) with different scenarios and compare the results with those of our analytic model. Random geometric networks have been used to represent network topologies in our simulation to ensure spatial homogeneity and relativity of MAG's and NAP's positions in space. Various network topology sizes with different number of

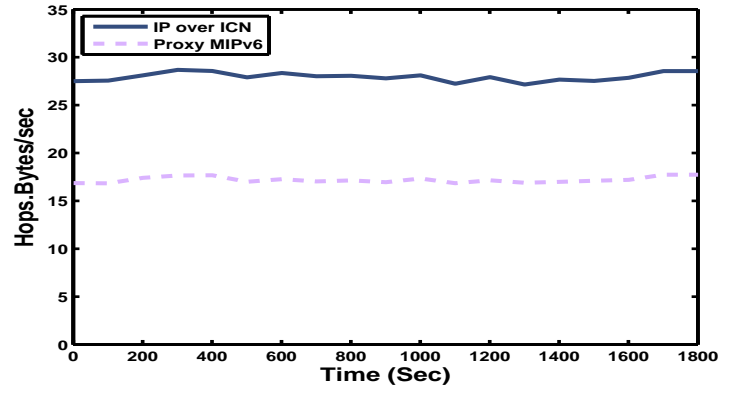
nodes (MAG's and NAPs) have been simulated with varying node degree (neighbour connectivity). Both MAG's and NAPs have been simulated using a circular coverage area with a radius of 500 m. The same central node was used to represent the LMA and TM/RV in all cases to ensure accurate cost comparisons. Random walk mobility model has been used to capture user mobility with various speed values ranging from pedestrians moving at a rate of 3 miles/hour to vehicles travelling at 70 miles/hour. User initial locations are randomly distributed using a uniform random distribution. In our traffic model we assume that all users in the network are exchanging video data at a rate of 1 Mbps. Every simulation experiment was run for 1800 seconds and repeated 20 times to reach a steady state and to ensure consistency among the obtained results.

6.1 Validating the Analytical Model Through Simulation

The first simulation experiment was conducted using the topology example in Fig. 5 in order to compare the results



(a) Packet Delivery Cost



(b) Signalling Cost

Fig. 13: Random Speed (3 - 70 miles/h) Simulation of 50 MNs with Average Cost using a Geometric Random Topology of 100 nodes.

with those obtained from the cost analysis functions and mobility model in the previous section. A single mobile node was simulated to move randomly with speed of 70 miles/h. Both the MN initial location and traversed paths were selected randomly from a uniform distribution. Fig. 11 shows both the accumulative packet delivery and signalling costs for Proxy MIPv6 and IP-over-ICN, and it is clear from the results in Fig. 11a that Proxy MIPv6 imposes a higher packet delivery cost of more than three times that of IP-over-ICN reaching about 15×10^8 Hops.Bytes due to the longer traffic paths imposed by using a central LMA. Also from Fig. 11b it can be seen that IP-over-ICN imposes higher signalling cost than Proxy MIPv6 reaching more than 8×10^4 Hops.Bytes compared to about 5×10^4 Hops.Bytes incurred by Proxy MIPv6. This is due to the fact that IP-over-ICN uses source routing and therefore imposes more signalling messages to secure delivery path trees to the traffic source during mobility. But despite the signalling cost results, the high difference in magnitude of packet delivery cost between Proxy MIPv6 and IP-over-ICN indicates that IP-over-ICN highly outperforms Proxy MIPv6 in the total cost. Fig. 11 also shows both simulation vs modelling results for the example topology in Fig. 5 and manifests a high degree of similarity in the figures resulting from both methods which proves the validity and accuracy of the performed analysis.

6.2 Mobile Node Speed Variation

The second simulation experiment was conducted using random geometric networks of 100 nodes with average connection degree of 4 neighbours (between 1 and 8 neighbours for every NAP/MAG in the network). 50 MNs were simulated to roam freely and randomly within the network domain. Various node speeds have been used in this experiment ranging between pedestrian speed of 3 miles/h and highway speed of 70 miles/hour. MN initial locations, traversed paths and speeds were all selected randomly from uniform distributions. Fig. 12 shows the average packet delivery and signalling costs respectively at 70 miles/h for both Proxy MIPv6 and IP-over-ICN. According to the figures, Proxy MIPv6 shows approximately double the packet delivery cost imposed by IP-over-ICN due to the central

traffic anchoring. And although IP-over-ICN shows higher signalling costs, the high difference in figures between packet delivery cost and signalling cost implies that IP-over-ICN requires half the total cost of Proxy MIPv6 in order to provide network enabled mobility support. Another simulation run is shown in fig. 13 using random MN speeds ranging from 3 to 70 miles/h. Both figures 13a and 13b clearly show that the same difference in performance is observed between IP-over-ICN and Proxy MIPv6 in terms of packet delivery and signalling costs respectively although random MN speeds have been simulated. Figures 14 and 15 show the total incurred mobility signalling and packet delivery costs respectively when different MN speeds are simulated individually. It can be seen from the results that mobility signalling cost has a positive relation with MN speed ranging from only 3720 and 5593 Hops.Bytes for Proxy MIPv6 and IP-over-ICN respectively with MN speed of 3 miles/h to about 1.3×10^6 and 2×10^6 Hops.Bytes for Proxy MIPv6 and IP-over-ICN respectively with MN speed of 70 miles/h. On the other hand, the packet delivery cost is not influenced by any speed changes as seen in figure 15.

6.3 Network Topology Size Variation

The third simulation experiment was conducted using different network sizes to show how network dimensions can effect the total cost. Random geometric networks ranging from 100 up to 10000 nodes have been simulated with average connection degree of 4 neighbours for every NAP/MAG in the network. 50 MNs were simulated to roam freely and randomly within the network domain with speed of 70 miles/h. Fig. 16 shows the total cost (packet delivery + signalling) for both Proxy MIPv6 and IP-over-ICN for each of the simulated topology sizes. It can be seen from the bar trends that IP-over-ICN always outperforms Proxy MIPv6 in terms of the total cost required to support NetLMM with a gain factor of at least 1.8 over Proxy MIPv6.

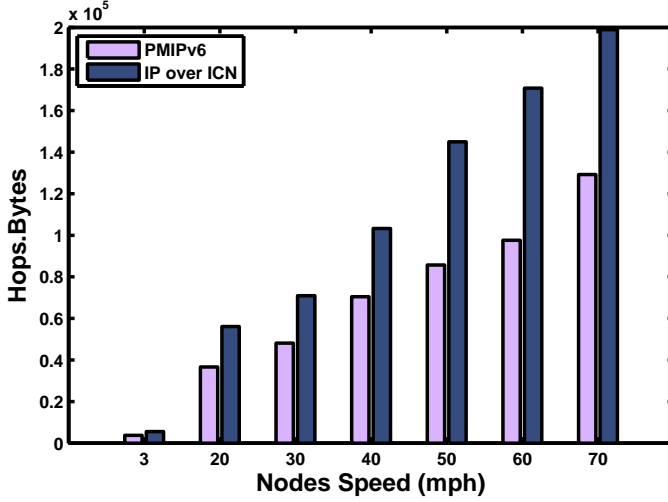


Fig. 14: Mobility Signalling Cost with Different Nodes Speed

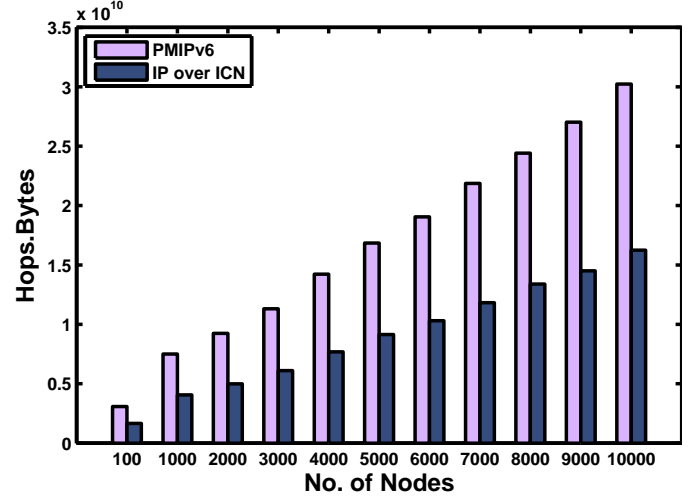


Fig. 16: Total Cost with Different Network Topology Sizes

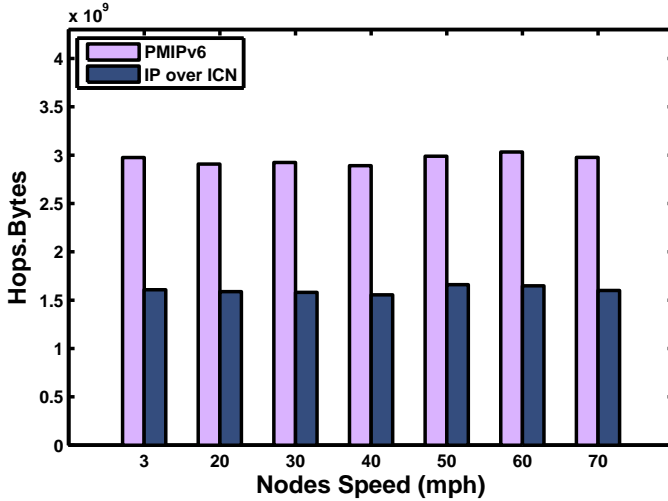


Fig. 15: Mobility Packet Delivery Cost with Different Nodes Speed

7 RELATED WORK

IP mobility for IPv6 hosts is specified by the IETF in Mobile IPv6 [RFC3775] [27]. Mobile IPv6 requires client functionality in the IPv6 stack of a mobile node. Exchange of signalling messages between the mobile node and home agent allows the IP host to send IP mobility management messages to the home agent, which is located in the network. Further extensions have been proposed by IETF to support network-based mobility and eliminate involving the mobile node in the exchange of signalling messages between itself and the home agent. A proxy mobility agent in the network performs the signalling with the home agent and does the mobility management on behalf of the mobile node attached to the network. This protocol is referred to as Proxy Mobile IPv6 (PMIPv6) [RFC5213] [7]. On the other hand, 3GPP specifies the General packet radio service (GPRS) Tunneling Protocol (GTP) [11] to support mobility. GTP is an important IP/UDP based protocol used in GSM, UMTS and LTE core networks. It is used to encapsulate user data when passing through core network using GTP-

U and also carries bearer specific signalling traffic between various core network entities using GTP-C. Also in efforts to significantly improve handover between heterogeneous network technologies IEEE standards association has developed 802.21 [28] that defines a media-independent handover (MIH) framework. The standard defines the tools required to exchange information, events, and commands to facilitate handover initiation and handover preparation. A large number of researches have focused on amendments, improvements and cost evaluation of the standards mentioned previously, we summarize a number of them below.

In [29] the authors propose an analytical framework based on IP-based cellular networks. They investigate the performance of PMIPv6 with respect to various metrics, including signalling cost, handover delay and packet loss, and compare it with host-based mobility management protocols, such as Mobile IPv6, FMIPv6 and HMIPv6. They demonstrated through simulation the salient performance of PMIPv6. In [1] the authors have developed an analytical cost model for evaluating the performance of the existing IP mobility management protocols including Proxy Mobile IPv6 (PMIPv6); they are analysed and compared in terms of signalling cost, packet delivery cost, tunnelling cost, and total cost. The conducted results identify each mobility management protocol's strengths and weaknesses that could be used to facilitate decision-making for consumer network design. In [30] the authors propose a base solution (BS) and a direct multicast routing scheme (DMRS) for multicast source mobility in PMIPv6 networks. In order to transmit multicast data through the PMIPv6 tunnel, they adopt the Multicast Listener Discover (MLD) Proxy function in the BS. In the DMRS, locally optimized routing for traffic flows are provided. The performance of the proposed schemes is evaluated by theoretical analysis and implementation. Their results show that the proposed schemes outperform the previous solutions in terms of the signalling cost and the BS has lower multicast handover delay than the DMRS. In [31] the authors propose an IEEE 802.21 Media Independent Handover (MIH) functionality assisted Proxy Mobile IPv6 (PMIPv6) mechanism for reducing handover latency and signalling cost in heterogeneous wireless networks. The pro-

posed mechanism comes to support fast vertical handover for the mobile node (MN) irrespective of the presence or absence of MIH functionality as well as IP mobility functionality. The base station with MIH functionality performs handover on behalf of the MN. The analytical evaluation shows that the proposed mechanism can outperform the existing mechanism in terms of handover latency and total number of over the air signalling messages.

8 DISCUSSION AND COMPARISON OF NETLMM MOBILITY APPROACHES

A key fact of the current Internet is that it was built on an architecture that exploits end host IP addresses as communication endpoints. This has been a fundamental obstruction in supporting many of the features and services that came to necessity afterwards including end user mobility [19]. Patches to the Internet architecture, including Proxy MIPv6 provide network enabled mobility support for IPv4/IPv6 networks but this comes with considerable cost. Proxy MIPv6 uses GRE or IP-in-IP tunnelling between the LMA and MAG to deliver traffic destined to a MN's IP address encapsulated within a tunnel whose endpoints hold the addresses of the participating LMA and MAG. This approach has several drawbacks including limited scalability when using a single centralized LMA to manage tunnel creation/deletion, also low bandwidth efficiency due to the tunnelling packet overhead. Another drawback is non optimum packet delivery routes since all mobile traffic has to pass through a central anchor point. And last but not least, injecting extra traffic into the network due to the triangular (SMAG - LMA - DMAG) communication strategy [9]. Other recent proposals such as Distributed Mobility Management (DMM) efforts [32] [33] that claim to solve Proxy MIPv6 drawbacks by distributing the LMA functionality into the network edges, still perform traffic tunnelling and anchoring in a localized manner which does not eliminate the traffic overhead imposed to support mobility. IP-over-ICN on the other hand provides a natural solution to the drawbacks mentioned above by exploiting the ICN core semantics of naming information items being transferred rather than the location dependant end host communication used in current IP networks. ICN decouples request resolution from data transfer in both time and space representing active user sessions as information publications/subscriptions. This method provides improved scalability and bandwidth efficiency compared to Proxy MIPv6 as no tunnelling is required for traffic delivery. Also optimum packet routing is achieved from source to destination utilizing shortest path routes supplied by the TM which ensures minimum duplicate traffic flowing through network core. In terms of network complexity, Proxy MIPv6 increases network fragility due to the explosive growth of the binding table size in a single LMA for all MNs in the domain. And also imposes processing complexity at the network core (LMA) and edges (MAG's) to support protocol functionality. On the other hand, IP-over-ICN increases network heterogeneity by using two different mediation technologies (IP and ICN) and also imposes processing complexity at the network edges (NAPs) for interfacing and address mapping [34]. But when it comes to end to end

transparency, both Proxy MIPv6 and IP-over-ICN violate this property. Although they do provide user experience transparency which is an essential goal for mobility support, they don't provide actual network addressing transparency which requires unaltered mechanisms of packets flow and logical addressing between source and destination [35]. This can be considered as an increasing complexity factor. Hence from all the aforementioned properties, it can be concluded that IP-over-ICN does not impose significant network complexity over Proxy MIPv6 although it shows significant gain in total cost for mobility support throughout the network [36] [37].

9 CONCLUSION

With the dominance of mobile internet traffic today, network enabled mobility management is an appealing property for network operators due to the fact that no user equipment changes are needed to support mobility in addition to reduced mobility signalling and improved handover performance. In this paper, network enabled mobility management has been proven to be possible with approximately half the cost of current available solutions such as Proxy MIPv6 when using an IP-over-ICN approach with IP endpoints and an ICN core. Using ICN in the core network ensures optimum shortest path packet delivery facilitated by the TM rather than the traffic anchoring and tunnelling methods used by current available solutions that lead to using non optimum roots for packet delivery. Although IP-over-ICN imposes higher mobility signalling, high gains in packet delivery and total costs have been shown in the conducted simulations even with high mobility rate environments. This proposed mobility solution can be facilitated by any other mediation such as software defined networks (SDN) using a similar infrastructure.

REFERENCES

- [1] J.-H. Lee, T. Ernst, and T.-M. Chung, "Cost analysis of ip mobility management protocols for consumer mobile devices," *Consumer Electronics, IEEE Transactions on*, vol. 56, no. 2, pp. 1010-1017, 2010.
- [2] N. Fotiou, K. Katsaros, G. C. Polyzos, M. Särelä, D. Trossen, and G. Xylomenos, "Handling mobility in future publish-subscribe information-centric networks," *Telecommunication Systems*, vol. 53, no. 3, pp. 299-314, 2013.
- [3] C. V. N. Index, "Forecast and methodology, 2014-2019 white paper," Technical Report, Cisco, Tech. Rep., 2015.
- [4] C. J. Bernardos, M. Gramaglia, L. M. Contreras, M. Calderon, and I. Soto, "Network-based localized ip mobility management: Proxy mobile ipv6 and current trends in standardization," *Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications (JoWUA)(Special issue: Advances in Wireless Mobile and Sensor Technologies)*, vol. 1, no. 2/3, pp. 16-35, 2010.
- [5] I. Soto, C. J. Bernardos, M. Calderón, and T. Melia, "Pmip6: A network-based localized mobility management solution," *The Internet Protocol Journal*, vol. 13, no. 3, pp. 2-15, 2010.
- [6] K.-S. Kong, W. Lee, Y.-H. Han, M.-K. Shin, and H. You, "Mobility management for all-ip mobile networks: mobile ipv6 vs. proxy mobile ipv6," *Wireless Communications, IEEE*, vol. 15, no. 2, pp. 36-45, 2008.
- [7] S. Gundavelli, A. N. W. G. Proxy Mobile IPv6 *et al.*, "Rfc 5213, aug. 2008, 93 pages."
- [8] J.-H. Lee, J.-M. Bonnin, I. You, and T.-M. Chung, "Comparative handover performance analysis of ipv6 mobility management protocols," *Industrial Electronics, IEEE Transactions on*, vol. 60, no. 3, pp. 1077-1088, 2013.

- [9] F. Giust, C. Bernardos, and A. La Oliva, "Analytic evaluation and experimental validation of a network-based ipv6 distributed mobility management solution," *Mobile Computing, IEEE Transactions on*, vol. 13, no. 11, pp. 2484–2497, 2014.
- [10] R. Wakikawa and S. Gundavelli, "Ipv4 support for proxy mobile ipv6," 2010.
- [11] N. F. V. NFV, "Draft etsi gs nfv-rel 001 v0. 1.3 (2014-06)," 2014.
- [12] I. Ali, A. Casati, K. Chowdhury, K. Nishida, E. Parsons, S. Schmid, and R. Vaidya, "Network-based mobility management in the evolved 3gpp core network," *Communications Magazine, IEEE*, vol. 47, no. 2, pp. 58–66, 2009.
- [13] G. Xylomenos, C. N. Ververidis, V. A. Siris, N. Fotiou, C. Tsilopoulos, X. Vasilakos, K. V. Katsaros, and G. C. Polyzos, "A survey of information-centric networking research," *Communications Surveys & Tutorials, IEEE*, vol. 16, no. 2, pp. 1024–1049, 2014.
- [14] "Pursuit project." [online]. available: <http://www.fp7-pursuit.eu>.
- [15] "Fp7 4ward project." [Online]. Available: <http://www.4ward-project.eu/>
- [16] "Fp7 comet project. [online]. available: <http://www.comet-project.org/>."
- [17] "Fp7 convergence project." [Online]. Available: <http://www.ictconvergence>
- [18] D. Trossen and G. Parisi, "Designing and realizing an information-centric internet," *Communications Magazine, IEEE*, vol. 50, no. 7, pp. 60–67, 2012.
- [19] G. Xylomenos, X. Vasilakos, C. Tsilopoulos, V. A. Siris, and G. C. Polyzos, "Caching and mobility support in a publish-subscribe internet architecture," *Communications Magazine, IEEE*, vol. 50, no. 7, pp. 52–58, 2012.
- [20]
- [21] M. J. Reed, "Traffic engineering for information-centric networks," in *Communications (ICC), 2012 IEEE International Conference on*. IEEE, 2012, pp. 2660–2665.
- [22] R. Droms, "Dynamic host configuration protocol," 1997.
- [23] L. Li, D. Alderson, W. Willinger, and J. Doyle, "A first-principles approach to understanding the internet's router-level topology," *ACM SIGCOMM Computer Communication Review*, vol. 34, no. 4, pp. 3–14, 2004.
- [24] T. Choi, L. Kim, J. Nah, and J. Song, "Combinatorial mobile ip: a new efficient mobility management using minimized paging and local registration in mobile ip environments," *Wireless Networks*, vol. 10, no. 3, pp. 311–321, 2004.
- [25] L. Kleinrock, "Queueing systems," 1975.
- [26] Z. Yan, J.-H. Lee, and Y. Tian, "Localized paging scheme in pmipv6," in *Innovative Mobile and Internet Services in Ubiquitous Computing (IMIS), 2013 Seventh International Conference on*. IEEE, 2013, pp. 24–28.
- [27] D. Johnson, C. Perkins, J. Arkko et al., "Rfc 3775: Mobility support in ipv6," *IETF*, June, 2004.
- [28] K. Taniuchi, Y. Ohba, V. Fajardo, S. Das, M. Tauil, Y.-H. Cheng, A. Dutta, D. Baker, M. Jain, and D. Famolari, "Ieee 802.21: Media independent handover: Features, applicability, and realization," *Communications Magazine, IEEE*, vol. 47, no. 1, pp. 112–120, 2009.
- [29] Y. Li, H. Su, L. Su, D. Jin, and L. Zeng, "A comprehensive performance evaluation of pmipv6 over ip-based cellular networks," in *Vehicular Technology Conference, 2009. VTC Spring 2009. IEEE 69th*. IEEE, 2009, pp. 1–6.
- [30] L. Wang, S. Gao, H. Zhang, T. C. Schmidt, and J. Guan, "Multicast source mobility support schemes in pmipv6 networks," in *Vehicular Technology Conference (VTC Fall), 2013 IEEE 78th*. IEEE, 2013, pp. 1–7.
- [31] P. S. Kim, M. S. Jang, and E. H. Lee, "An ieee 802.21 mih functionality assisted proxy mobile ipv6 for reducing handover latency and signaling cost," in *Information Technology: New Generations (ITNG), 2013 Tenth International Conference on*. IEEE, 2013, pp. 692–695.
- [32] D. Liu and P. Seite, "Distributed mobility management: Current practices and gap analysis," 2015.
- [33] C. J. Bernardos, A. De la Oliva, and F. Giust, "A pmipv6-based solution for distributed mobility management," 2013.
- [34] W. Willinger and J. Doyle, "Robustness and the internet: Design and evolution," *Robust-Design: A Repertoire of Biological, Ecological, and Engineering Case Studies*, pp. 231–272, 2002.
- [35] B. Carpenter, "Internet transparency," RFC 2775, February, Tech. Rep., 2000.
- [36] D. Alderson, L. Li, W. Willinger, and J. C. Doyle, "Understanding internet topology: principles, models, and validation," *Networking, IEEE/ACM Transactions on*, vol. 13, no. 6, pp. 1205–1218, 2005.
- [37] J. C. Doyle, D. L. Alderson, L. Li, S. Low, M. Roughan, S. Shalunov, R. Tanaka, and W. Willinger, "The robust yet fragile nature of the internet," *Proceedings of the National Academy of Sciences of the United States of America*, vol. 102, no. 41, pp. 14 497–14 502, 2005.